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Marszal, Anna Joanna; Stoustrup, Jakob; Widén, Joakim; Le Dréau, Jérôme

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Anna Marszal-Pomianowska[1], Jakob Stoustrup[2], Joakim Widén[3], Jérôme Le Dréau[4]
[1]Department of Civil Engineering, Aalborg University, Aalborg, Denmark
[2]Department of Electronic Systems, Aalborg University, Aalborg, Denmark
[3]Department of Engineering Sciences, Uppsala University, Uppsala, Sweden
[4]Department of Engineering Sciences, University of La Rochelle, La Rochelle, France

Abstract

Buildings can facilitate a safe and uninterrupted transition from traditional production-respond to future demand-respond energy systems by delivering flexibility service to the system with smart control of their energy loads. Current methods used for building design and performance evaluation are focused on minimizing the building energy use and do not quantify the flexibility potential of the buildings. As the energy flexibility is of interest for the built and network environment, this paper presents a simple energy flexibility factor, which combines the needs of both and can be easily applied during the simulation/design and operation phases of a building.

Introduction

Today's energy systems are moving away from fossil fuel dependency towards fully based on renewable energy source (RES). This transition goes parallel with the increased electrification of the demand side, e.g. replacement of traditional cars with electrical vehicles or displacement of fossil fuel heating systems, such as gas or oil boilers with heat pumps, DEA (2014) and Eurostat (2016). These changes impose new challenges in energy system management and operation, such as variability and fluctuations of energy supply, grid operation at its "edge" and increased energy consumption during peak periods, Moslehi et al. (2010). In order to address these challenges, the future energy systems are expected to take a major paradigm shift from traditional production-respond to future demand-respond systems, Lund et al. (2015) and Baillieul et al. (2016). As buildings account for approximately 40% of the annual energy consumption worldwide, they have a significant role to play in safe and uninterrupted operation of the future energy system, namely they can deliver flexibility service to the system by smart control of their energy loads. A building can supply flexibility services by several means e.g. utilization of thermal mass, adjustability of HVAC systems, e.g. heating system, use of electric vehicles and modulation of plug-loads, as presented by Clement-Nyns et al. (2010), Diaz (2014), Le Dreau et al. (2016), Paatero et al. (2006) and Reynders et al. (2013).

Currently, commonly applied methods used for building design and performance evaluation are focused on minimizing the building energy use, e.g. CEN, EN 15603 (2008). They do not address the new features of future buildings, i.e. the active participation at the energy market. However, the research environment already recognizes this issue and has presented it Lopes et al. (2016). Different methodologies to quantify the energy flexibility potential of a building(s) are present in the literature. There are two general approaches for quantifying energy flexibility. In the first approach, energy flexibility is related to a specific energy system and/or market context, e.g. price signal. An example could be the flexibility factor proposed by Le Dreau et al. (2016) which quantifies to what extent energy flexibility achieved by activation of thermal mass can be used to shift energy from high- to low-price periods. The second approach quantifies energy flexibility that a building can offer to the energy system without considering if the system needs or uses the available flexibility. This approach is reflected in the methodologies proposed by De Coninck et al. (2013), De Coninck et al. (2016), D'hulst et al. (2015), Le Dreau et al. (2016), Nuytten et al. (2013), Oldewurtel et al. (2013), Reynders et al. (2015) and Six et al. (2011).

The energy flexibility of buildings is of interest for both the built and network environment. Thus, the quantification method should be developed so it is useful for both parties, i.e. provides needed information about flexibility for both building and network designers and/or operators. Therefore, the objective of this paper is to present an energy flexibility factor, which combines both approaches. It quantifies building flexibility independently for the market context and the specifics of the energy system as well as it is useable for parties, e.g. balancing responsible parties (BRP) involved in regulation market and thus interested in the flexibility potential of the building stock, which can be used to solve operational bottlenecks of the future demand-respond energy system. The aim is to facilitate engineers and architects in designing grid-ready buildings and to give the information to network designers/operators about what are the possible operational conditions of a given network. Moreover, it is thought that the method is easy to apply, based on traditionally performed tasks during the design phase, such as dynamic building simulations, and it can quantify the energy flexibility potential of any applied demand-side-management (DSM) strategy. This paper investigates two DSM strategies: a) shift in time of the plug-loads and b) activation of the building thermal mass to modulate the energy demand of the heating system and the resulting heat pump electricity use.

Methodology

The analysis is conducted in three parts, cf. Figure 1. The first part describes the models used to create high-resolution profiles of plug-loads and heat pump electricity consumption. The second part presents the control strategies for plug-loads and heat pump. Finally, the third part explains the flexibility factor and its practical application.
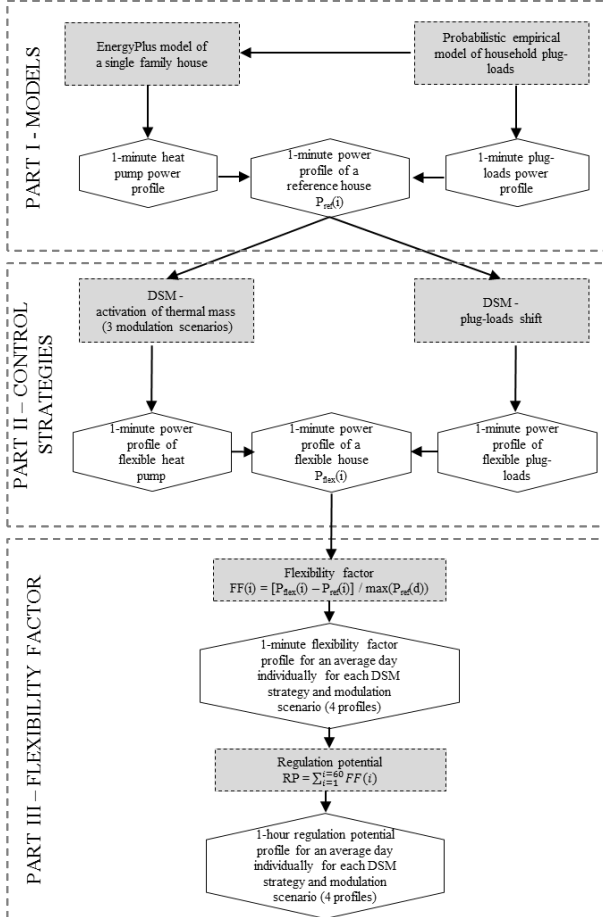

Figure 1: Overview of the methodology steps.

Models

Plug-loads model

The one-minute profiles of domestic base load are created using a "bottom-up" modeling approach. The model uses individual appliance characteristics and its cycle of power use as a basic building block. As described by Marszal-Pomianowska et al. (2016), the model is developed in a Matlab environment and validated in order to generate plug-loads profiles of the Danish single-family houses. Moreover, the model has some unique features, namely it generates the power profiles with respect to the number of occupants in the household (from 1 to 5 occupants) and their attitude towards energy use/savings (interested, neutral, disinterested). The procedure is as follows. Firstly, the number of occupants and their attitude towards energy savings is given for each house. These inputs together with the penetration level specified for each appliance are the background data for equipping each customer with a set of appliances. Secondly, the model generates

the electricity load profile individually for each appliance. To do so, for each minute, a random number P is generated between 0 and 1 and then P_{on} is calculated using (1). P_{on} also varies between 0 and 1 and defines whether or not the appliance switches ON. When the switch ON event occurs at the time step t, $P_{on} > P$, the operation cycle starts and, therefore, the cycle of power consumption is added to the load profile of the appliance. The operation cycle finishes at time $t + t_{cycle}$. During the time the appliance is ON, the P_{on} is not calculated.

$$P_{on}(a,w,h,d,n,c,\Delta t) = P_{act}(a,h,d) \cdot f(a,d,n,c) \cdot F_{soc} \cdot P_{season}(w) \cdot P_{step}(\Delta t) \qquad (1)$$

where,

P_{act} is the probability to have activity, a refers to the appliance; w refers to week number; h refers to the hour of the day; d indicates whether is weekday or weekend, n is number of occupants; c indicates the type of occupants; f refers to the frequency of use; F_{soc} is a social random factor which accounts for short-term and sudden variations of the household electricity use due to e.g. weather fluctuations such like heavy rain or very sunny winter afternoon, affecting the washing needs and/or the lighting, local or international events, e.g. TV shows or energy-saving initiative affecting the time of using household entertainment devices; P_{season} is the seasonal probability which models the sinusoidal pattern of the seasonal, long-term variations in household electricity use; and P_{step} is step scaling factor and depends on the time step Δt.

Finally, by summing up the power demands of all appliances installed within a given household, it is possible to calculate the total power profile for the given household. The model normally operates with one-minute resolution; however, profiles with other resolutions, e.g. ten minutes or one hour, can also be created following the same methodology. It should be mentioned that this study will assume a constant household size of 3 persons.

Heat pump profiles

In order to test the flexibility of various houses, two types of residential buildings have been selected in the Danish building stock, Kragh et al. (2014). The buildings will represent an "average" existing building (1980s house) and a state-of-the-art building (passive house). Figure 2 presents the 3D models of both houses. The first house corresponds to a non-renovated single-family house from the 1980s, characterized by a high heating need (around 155 kWh/m² year). The cavity walls are insulated with 12.5 cm of stone wool and the attic with 30 cm. The glazed area is reduced to fit with the 1978 building regulation, and the windows are made of double-glazing. The house is naturally ventilated. The second house is based on a house built according to the passive house standards. The heating need of this state-of-the-art building is around 13 kWh/m² year. The envelope is light and highly-insulated (45 cm in the floor, walls and ceilings), and a heavy concrete core ensures a sufficient amount of thermal mass. The living

room is equipped with large triple-layer windows. The level of infiltration is low and the ventilation system is equipped with heat recovery. Table 1 and Le Dreau et al. (2016) provide more details. Families of three persons are assumed to live in the houses. The models have been developed using EnergyPlus v. 8.1 (2013), and each building is modelled by 8 thermal zones in order to properly account for differences between rooms.
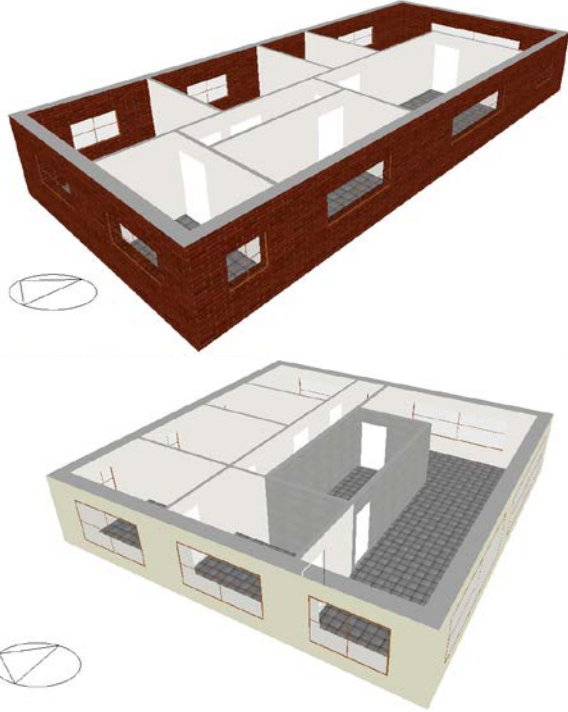

Figure.2: 3D models of simulated buildings: top) house from the 1980s, bottom) passive house.

These two houses are heated up by heat pumps, connected either to radiators in the 1980s house and to an underfloor heating system in the Passive House. Both heating systems are water-based, and the sizing has been performed according to the Danish guidelines (with an oversizing factor of +25 %). As the sizing depends on the building type, the heating power varies between 25 W/m² for the passive house and 75 W/m² for the 1980s house. The control is room-based with a (default) temperature set-point of 22°C (neutral sensation of thermal comfort according to EN ISO 7730 (2005)). In the BES tool, the heat exchange between the radiator and the thermal zone is modeled using a UA heat exchange coefficient, and the heat transfer within the baseboard is evaluated by the effectiveness-NTU heat exchanger method applied in EnergyPlus v. 8.1 (2013). The model assumes no heat storage in the baseboard unit itself. The underfloor heating is modelled as a low temperature system, with a variable inlet water temperature (P-controller with a throttling range of 0.15 K). In the BES tool, pipes are modelled as 2D heat sources and the heat transfer within the hydraulic system is evaluated by the effectiveness-NTU heat exchanger method applied in EnergyPlus v. 8.1 (2013).

The heat pump is linked to vertical boreholes located at 100 m depth where the soil temperature is stable (equal to 10°C). The ground-loop heat exchanger model uses a set of non-dimensional temperature response factors – g-functions – that allows the calculation of the temperature change at the borehole wall in response to a step heat input as explained by Fisher et al. (2005). The heat pump is sized to cover the annual heat demand only for space heating and the heat demand for the domestic hot water is not accounted for. The heat pump delivers hot water to the building at different temperatures depending on the types of emitter and building (ranging from 30°C up to 70°C). The nominal Coefficient of Performance (COP) of the heat pump is 4.5 (1980s house) and 4.95 (passive house). The heat pump model uses manufactured published data to find the required parameter values for each component. The parameters are determined using a multi-variable optimization algorithm as explained by Fisher et al. (2005). The result extracted from the simulations is the total electricity use for heating, which accounts for both the electricity for the heat pump and other pumps.

Table 1: Building characteristics

		House from the 1980s	Passive house
Constructions	$UA_{building}$	171 W/K	62 W/K
	U_{floor}	0.31 W/m².K	0.07 W/m².K
	U_{walls}	0.32 W/m².K	0.09 W/m².K
	$U_{ceiling}$	0.16 W/m².K	0.08 W/m².K
	$U_{window} - g_{window}$	1.7 W/m².K – 0.63	0.78 W/m².K – 0.50
	Ratio: windows to gross area	17 %	27 %
	Heat capacity C_m	44 Wh/K.m² (light)	53 Wh/K.m² (medium)
Air flow	$ACR_{infiltration}$	0.2 ACH	0.07 ACH
	$ACR_{ventilation}$	0.4 ACH (natural)	0.4 ACH (mechanical)
	$\eta_{ventilation}$	-	80 %

Control strategies

As mentioned, this paper investigates two DSM strategies: a) activation of the building thermal mass to modulate the energy demand of the heating system and the resulting heat pump power use and b) shift in time of plug-loads. Both DSM strategies are responding to the direct price signal from the utility, thus they do not consider the influence of consumers' behaviour on loads. The price single is understood as an indicator for share of renewable energy in the energy system.

DSM of the heat pump: activation of thermal mass (DSM #1, #2, #3)

The reference scenario is a (default) temperature set-point of 22°C (neutral sensation of thermal comfort EN ISO 7730 (2005)). This reference electricity use is compared to the electricity use when DSM strategies

based on modulations of the heating set-point are applied. The objective is to decrease the electricity use during time of shortage and increase it during time of renewable energy surplus in the energy system while maintaining a good level of comfort within the building. In order to set the DSM strategies, three parameters need to be defined: the temperature range, the time and the duration of the modulations:

- The temperature variations should fit the normal level of expectation and be within the range of 22±2°C, EN ISO 7730 (2005)
- The duration of modulations should be chosen so as to minimize the deviation from optimal comfort. Based on an extensive study of the thermal response of buildings by Le Dreau et al. (2016), two durations have been defined: 4 to 6 hours for the 1980s house and 24 hours for the passive house. However, increase of the temperature set-point should be avoided in the passive house as it sometimes leads to overheating with a rule-based controller.
- The time of modulation is solely defined based on the grid status, which will be characterized by its spot price. The set-point can be increased during low price, decreased during high price and kept at its reference value (22°C) otherwise. A low price corresponds to a price lower than the first quartile (evaluated over two weeks). A high price corresponds to a price higher than the third quartile.

Based on these parameters, different rule-based controllers have been defined. For the 1980s house heated up by radiators:

- Reference scenario, with a constant set-point of 22°C
- Flex scenario # 1 (4 hrs conservation): the set-point is decreased by 2 K in periods with high prices, but for a maximum period of 4 hours. This modulation can be repeated over the day after a waiting period of 4 hours.
- Flex scenario # 2 (4 hrs storage and conservation): the set-point is decreased by 2 K in periods with high prices or increased by 2 K in periods with low prices, but for a maximum period of 4 hours. These modulations can be repeated over the day after a waiting period of 4 hours.
- Flex scenario # 3 (6 hrs storage and conservation): similar to Scenario # 2, but with 6 hrs.

For the passive house equipped with an underfloor heating system:

- Reference scenario, with a constant set-point of 22°C
- Flex scenario # 1 (12 hrs conservation): the set-point is decreased by 2 K in periods with high prices, but for a maximum period of 12 hours. This modulation can be repeated over the day after a waiting period of 12 hours.

- Flex scenario # 2 (24 hrs conservation): similar to Scenario # 1, but with 24 hrs.
- Flex scenario # 3 (24 hrs conservation / 1 hr storage): the set-point is decreased by 2 K in periods with high prices, but for a maximum period of 24 hours. This modulation can be repeated over the day after a waiting period of 24 hours. Moreover, the set-point can also be increased by 2 K in periods with low prices, but for a maximum period of 1 hour. This modulation can be repeated over the day after a waiting period of 1 hour.

The indoor temperature set-point is controlled through the external interface BCVTB tool, Wetter et al. (2015) and the thermal building simulations are done in EnergyPlus. As the phases of charges/discharges require a fine modelling of the heat transfer within the first centimetres of the walls, conduction is calculated using the Finite Difference Method, short time-step (2 minutes) and a fine discretization (space discretization of 3). Deviations have been observed when using the conduction transfer function (CTF) or a too coarse grid.
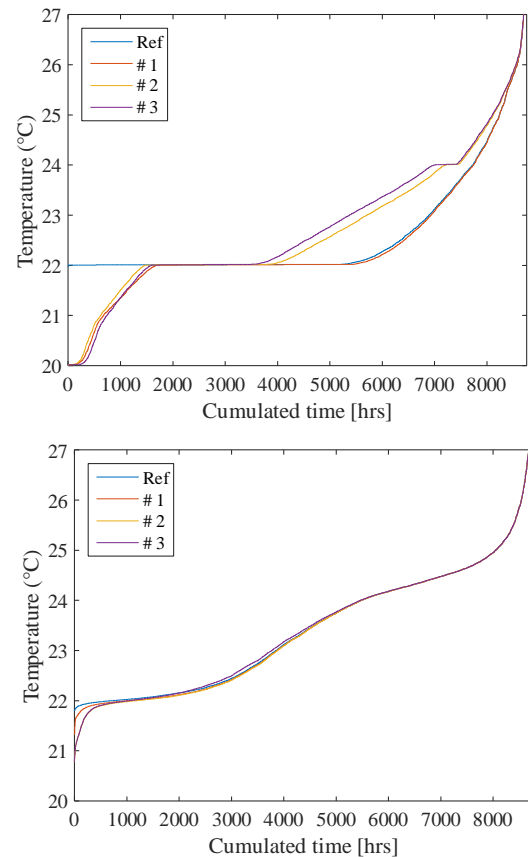

Figure 3: Cumulative temperature for the whole year in the house from 1980s (top) and passive house (bottom) for a reference and three flex scenarios.

Figure 3 presents the distribution of the operative temperature in the 1980s and the passive house. In both houses, the requirements for the Category II thermal comfort, corresponding to temperature range 20-25°C in winter and 23-26°C in summer) are met for all flex scenarios. The very few hours above 26°C – around 2.5% of the time for both houses – happen during the

summer time when the outdoor temperature is high, close to 30°C, and there is no heating demand and thus the heat pump is in "off" mode. The analysis of operative temperature only during the heating season – the period with highest utilization of heat pump and thus biggest flexibility potential – indicates that the users' thermal comfort is not jeopardized and stays within the normal level of expectation.

DSM of the plug-loads (DSM #4)

Optimal load shifting of dishwashers, washing machines and dryers, corresponding on average to 18% of the household electricity use, was simulated with a heuristic method previously developed by Widén (2014) for studying load shifting schemes in large sets of households. In this algorithm, each individual appliance load cycle in a monitored or simulated load profile is identified as a connected series of power consumption values > 0 and is shifted over a defined time window in order to maximize the economic benefit, based on the buying cost for electricity. The algorithm loops through all minutes of the time window, a day, and finds the optimal new starting time of each appliance by calculating the cost for purchased electricity over the whole load cycle and choosing the one with the lowest cost.

In mathematical terms, when a specific scheduled starting time t for an appliance is evaluated, the load profile of the appliance $L_a(t)$, …, $L_a(t + T - 1)$, where T is the number of time steps in the load cycle, is added to the existing load profile without the appliance. The result is an increase of the purchased electricity over these time steps. This cost increase is as follows:

$$\Delta C = \sum_{k=t}^{t+T-1} L_a(k)C_b(k) \qquad (2)$$

where,

C_b is the buying price for electricity. The chosen starting time is the one resulting in the smallest ΔC.

This is done for each appliance load cycle L_a in turn. Thus, it does not consider all possible combinations of appliance schedules, which could amount to a very large number. However, as described by Widén (2014) this limitation has a very insignificant impact on the results. The optimal scheduling of the appliances was done with respect to the hourly NordPool day-ahead spot market prices for Denmark in 2009, assuming a constant buying price for electricity within each hour. The loads were only rescheduled over the day to which they originally were scheduled. Widén (2014) has the exact algorithm and a more comprehensive discussion about the methodology.

Flexibility factor

As mentioned in the introduction, the main idea behind the flexibility factor is to have a parameter that the building and energy sector and parties interested in the energy flexibility of a building can use. Moreover, the aim is to create a simple factor that will not extend the already time and resource demanding building design process, but can be calculated based on traditionally conducted studies during building design, i.e. dynamic building simulations. For the power network operators, the peak power of a customer and its possible decrease/increase is key information. For the BRP, which operates on an hourly basis, a day is an operational timeframe according to Energinet.dk. Therefore, the proposed flexibility factor (FF) in a simple way illustrates the ability to decrease or increase power use at a given time step in relation to the reference daily peak power. If the power use is similar before and after application of flexibility measures, the factor is 0 and there is no potential to change the daily peak power at the given time step. If power use increases, the factor is above 0 and the FF value indicates how much the daily peak power can increase at the given time step. If the power use decreases, the factor is below 0 and the FF value indicates possible reduction of the daily peak power. There is no limit to the flexibility factor. Moreover, a graphical representation of the FF, i.e. a flexible curve, is a very informative way to present the flexibility potential of a building and hence the possible down or up regulation of the daily power peak for every time step.

$$FF(i) = [P_{flex}(i) - P_{ref}(i)] / \max(P_{ref}(d)) \qquad (3)$$

where,

P_{flex} is the power use of the flex-building; P_{ref} is the power use of the reference building, i is the time step; d is the day.

As mentioned, the regulation market and thus the BRPs operate on a 24h time horizon with 60 min intervals. Therefore, for the BRPs it is not the FF value for each time step, but an hourly integral of the FF for each hour of the day (day = 24 hours) that is interesting and useful information. In this paper, the hourly absolute integral of the flexibility factor is called regulation potential and is calculated according to (4) for each hour of the day and presented on a daily curve with 24 points. Regulation potential indicates how much the maximum daily power use can be changed over an hour; however, with no indication of down or up regulation.

$$RP(h) = \sum_{i=1}^{i=60} FF(i) \qquad (4)$$

where,

FF is flexibility potential; h is an hour.

Results

The objective of the proposed simple flexibility factor is to illustrate the ability of the applied DSM to shift electricity use over the day in relation to the daily peak power. For two topologies of a Danish single-family house, two DSM strategies are considered: a) activation of the building thermal mass to modulate the energy demand of the heating system and the resulting heat pump electricity use and b) shift in time of the plug-loads.

As shown on Figure 4, the flexibility factor in a sufficient manner gives the information of when and how much the peak power can be down- or upward
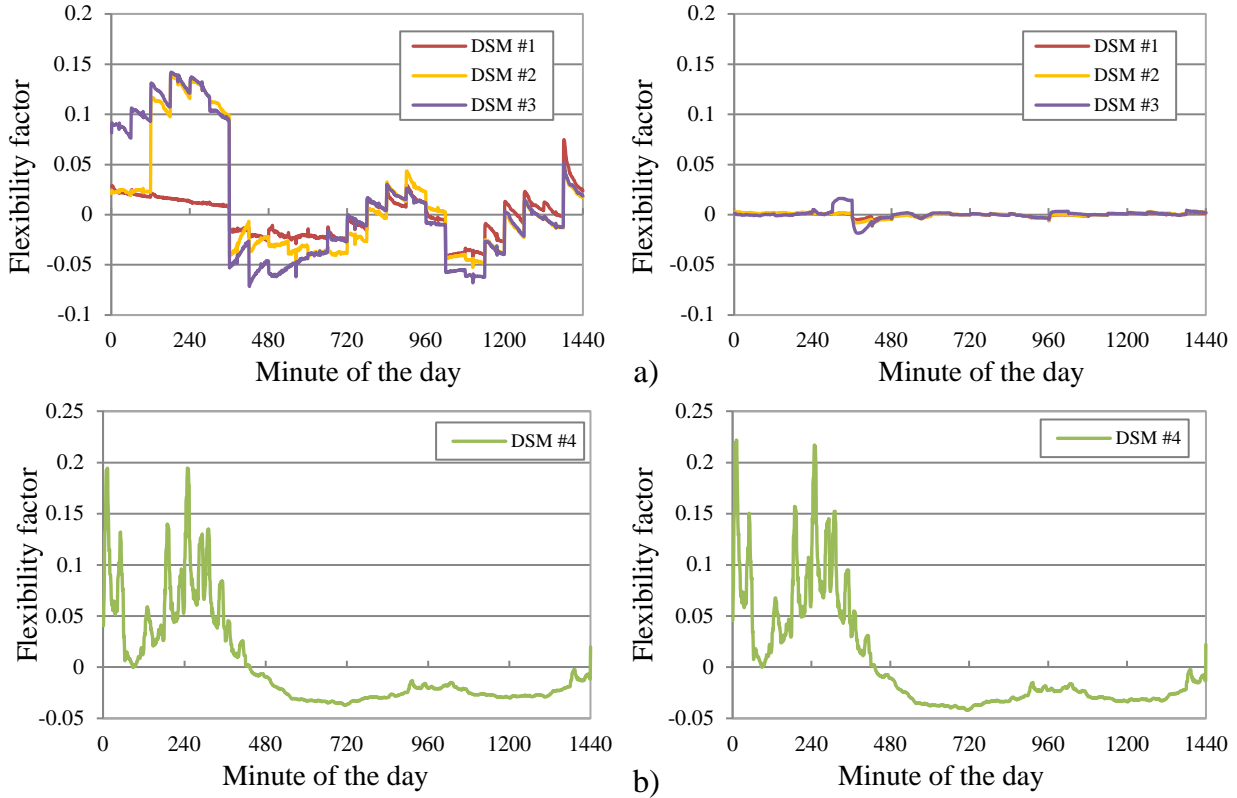
Figure 4: Flexibility factor for an average day for different DSM strategies a) thermal mass activation and b) plug-loads shift for the house from 1980's (left) and passive house (right).

regulated, thus how flexible the building is at the particular time slot, which for this analysis is 1 minute. The applied control of the plug-loads for both houses results in that the shift of power is from the daytime to the night time, i.e. flex factor above 0 during night and below 0 during day. It is a consequence of the price profiles that are applied for the control strategy. Between 24:00 and 8:00, the houses have a flexibility potential to upward regulate peak power up to 25%. During the day, the flexibility is only around 5%, but this is around the most critical periods of network operation, i.e. morning and afternoon peak. From the customer perspective, this means that if they want to supply this flexibility to the network all three appliances such like washing machine, dishwasher and dryer will have to operate during night time, which could be seen as a disturbance of consumers' life style and typical routines modelled by Marszal-Pomianowska et al. (2016). For the 1980s house, the flexibility achieved by the modulations of the heat pump electricity use follows a similar trend as plug-loads shift. It is clear that a longer set-point changes (DSM# 3) the results in higher flexibility potential to be utilized by the local network. The condition of 2K temperature variations has a strong influence on how much the heat pump can be down- and upward regulated. Bigger temperature swings would, on one hand, result in a higher flexibility factor but, on the other hand, lower costumers' thermal comfort. As the passive house has a low heat demand around 13 kWh/m2year, the heat pump power consumption is also

low and consequently the flexibility factor for an average day is close to 0.

Table 2: Overview of flexibility factor limits over the entire year for all DSM strategies (DSM# 1-3 thermal mass activation, DSM# 4 plug-loads shift) and both houses.

		Flexibility factor	
		min	**max**
House from 80s	DSM #1	-0.56	0.72
	DSM #2	-0.58	0.84
	DSM #3	-0.58	0.84
	DSM #4	-0.11	1.41
Passive house	DSM #1	-0.11	0.11
	DSM #2	-0.11	0.13
	DSM #3	-0.11	0.13
	DSM #4	-0.12	1.46

According to Table 2, the passive house activation of flex control of heat pump results in a peak power change of only ±10%, since the flexibility potential is much higher and reaches up to 84% in the house from the 1980s. The plug-loads shift has the same potential for both houses as they are both occupied by a family of 3 occupants with plug-loads power use of around 4000 kWh/year.

The absolute hourly integral of the FF over a day is very useful information for the BRP, which could collect such information from the number of houses in the neighbourhood /local power network, include it in their

balancing portfolio and thus activate the flexibility potential of the houses according to the system need as presented by Biegel et al. (2016). Figure 5 presents an example of daily profiles of regulation potential, which could be delivered to BRP by the building owners.
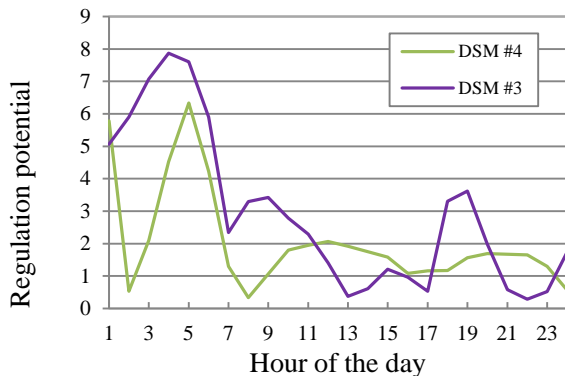

Figure 5: Regulation potential for house from 80s and flex scenario DSM #3 and plug-loads shift (DSM #4) for an average day.

Finally, Figure 5 and Table 2 show that the energy flexibility fluctuates over the day; it also varies over a week and year due to e.g. the state of the storage, the use of the building, the occupants' behaviour, the weather and thus cannot be described only with one value. Therefore, the energy flexibility of a house should rather be explained as a flexibility curve.

Conclusion

The energy flexibility available within the building sector is seen as one of the solutions for stable and uninterrupted operation of future smart energy systems. This new feature of future buildings calls for a new evaluation method which does not only evaluate energy performance but also flexibility potential and simultaneously gives valuable input for both building and network designers and/or operators. This paper aims at presenting a simple flexibility factor, which can assist engineers and architects in designing grid-ready buildings and give the information to network designers/operators about what the possible operational conditions of a given network configuration are.

The study of two Danish single-family houses and two DSM strategies has shown that the flexibility factor and its graphical representation, the flexible curve, are a very efficient way to quantify flexibility. The FF indicates the time and the scale of peak power change and the regulation direction, down or upward regulation. Together with the value of daily peak power it provides comprehensive information for network designers and BRP on how certain buildings can contribute to balancing the network. Moreover, the FF is easy to use for comparing influence of different DSM strategies on the flexibility potential of a building.

Furthermore, the analysis also indicated that houses with higher energy demand are expected to have higher flexibility potential. Therefore, it might be that the further tightening of energy frames for buildings is not needed, and instead the focus should be on evaluating whether or not the building has the ability to modulate its energy use and on how this can be utilized by the local network.

Finally, it should be mentioned that FF has its limitation, namely it relates only to the daily peak power. However, according to the network experts, the decrease or increase of the daily peak power and its time is the most useful information for stable system operation.

Acknowledgement

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